(4)

DNA-TR-88-94

FERROELECTRIC MEMORIES

G. C. Messenger
R & D Associates
P.O. Box 9695
Marina del Rey, CA 90295

20 June 1988

Technical Report

CONTRACT No. DNA 001-85-C-0022

Approved for public release;
distribution is unlimited.

THIS WORK WAS SPONSORED BY THE DEFENSE NUCLEAR AGENCY
UNDER RDT&E RMC CODE B4632D RD RC 00001 25904D.

Prepared for
Director
DEFENSE NUCLEAR AGENCY
Washington, DC 20305-1000

DISTRIBUTION LIST UPDATE

This mailer is provided to enable DNA to maintain current distribution lists for reports. We would appreciate your providing the requested information.

[ ] Add the individual listed to your distribution list.

[ ] Delete the cited organization/individual.

[ ] Change of address.

NAME:

ORGANIZATION:

OLD ADDRESS **CURRENT ADDRESS**

TELEPHONE NUMBER: ( )

SUBJECT AREA(s) OF INTEREST:

DNA OR OTHER GOVERNMENT CONTRACT NUMBER:

CERTIFICATION OF NEED TO KNOW BY GOVERNMENT SPONSOR (if other than DNA):

SPONSORING ORGANIZATION:

CONTRACTING OFFICER OR REPRESENTATIVE:

SIGNATURE

CUT HERE AND RETURN

Director
Defense Nuclear Agency
ATTN: TITL
Washington, DC 20305-1000

Director
Defense Nuclear Agency
ATTN: TITL
Washington, DC 20305-1000

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY N/A since Unclassified	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A since Unclassified	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) RDA-TR-135602-010	5. MONITORING ORGANIZATION REPORT NUMBER(S) DNA-TR-88-94
6a. NAME OF PERFORMING ORGANIZATION R & D Associates 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Director Defense Nuclear Agency
6c. ADDRESS (City, State and ZIP Code) P.O. Box 9695 Marina del Rey, CA 90295	7b. ADDRESS (City, State and ZIP Code) Washington, DC 20305-1000
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable) RAEE/Cohn	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER DNA 001-85-C-0022
8c. ADDRESS (City, State and ZIP Code)	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. 62715H; PROJECT NO. RD; TASK NO. RC; WORK UNIT ACCESSION NO. DH008670

11. TITLE (Include Security Classification)
FERROELECTRIC MEMORIES

12. PERSONAL AUTHOR(S)
Messenger, George C.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Technical	FROM 871101 TO 880301	880620	38

16. SUPPLEMENTARY NOTATION
This work was sponsored by the Defense Nuclear Agency under RDT&E RMC Code B4632D RD RC 00001 25904D.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	
20	3		Ferroelectric Memory, ...
12	6		Nonvolatile RAM

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Ferroelectric memory cells have been fabricated using a process compatible with semiconductor VLSI manufacturing techniques. The memory can be made NDRO for strategic and SDI systems using several techniques; the most practical is probably a rapid read/restore in combination with EDAC software. This memory can replace plated wire and will have substantial advantages in cost, weight, size, power and speed. It provides a practical cost-competitive solution to the need for nonvolatile RAM in all hardened tactical, avionic, and space systems.

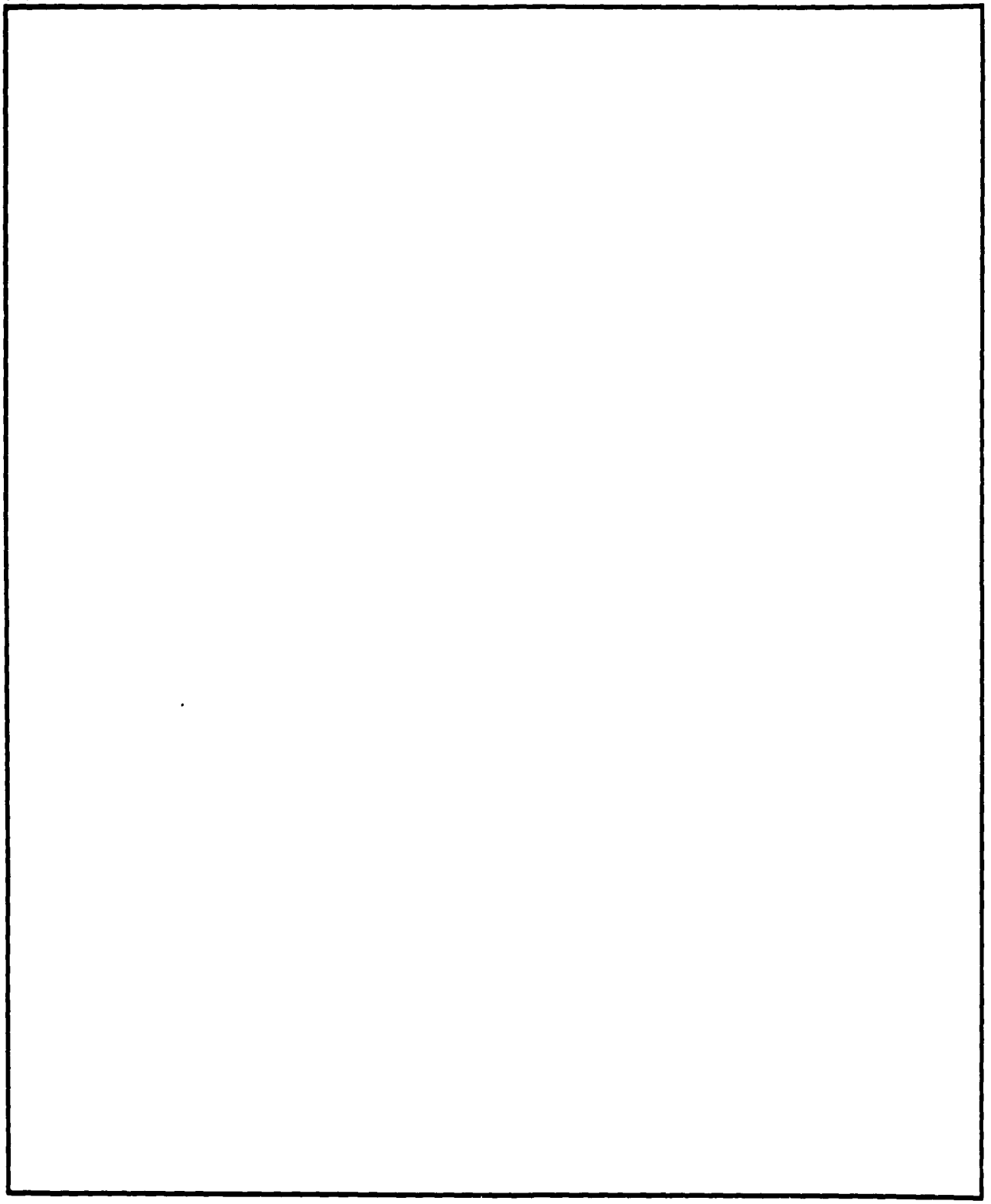
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL
Sandra E. Young	(202) 325-7042	DNA/CSTI

DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted. All other editions are obsolete.

UNCLASSIFIED

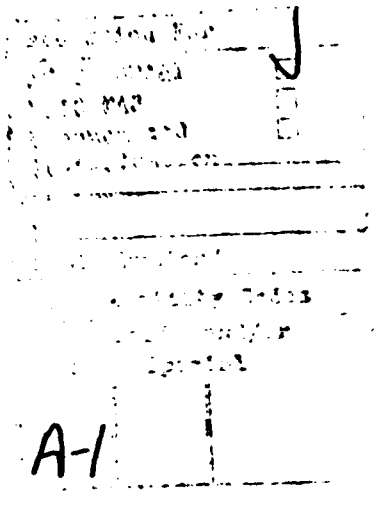
SECURITY CLASSIFICATION OF THIS PAGE



FERROELECTRIC MEMORIES: A POSSIBLE ANSWER TO THE HARDENED NONVOLATILE QUESTION

SUMMARY

Ferroelectric memory cells have been fabricated using a process compatible with semiconductor VLSI (Very Large-Scale Integration) manufacturing techniques which are basically nonvolatile and radiation hard. The memory can be made NDRO (Nondestructive Readout) for strategic and SDI (Strategic Defense Initiative) systems using several techniques; the most practical is probably a rapid read/restore in combination with EDAC software. This memory can replace plated wire and will have substantial advantages in cost, weight, size, power and speed. It provides a practical cost-competitive solution to the need for nonvolatile RAM in all hardened tactical, avionic, and space systems.



CONVERSION TABLE

Conversion factors for U.S. customary to metric (SI) units of measurement.

(Symbols of SI units given in parentheses)

To convert from	to	Multiply by
angstrom	meters (m)	1.000 000 X E -10
atmosphere (normal)	kilo pascal (kPa)	1.013 25 X E +2
bar	kilo pascal (kPa)	1.000 000 X E +2
barn	meter^2 (m^2)	1.000 000 X E -28
British thermal unit (thermochemical)	joule (J)	1.054 350 X E +3
calorie (thermochemical)	joule (J)	4.184 000
cal (thermochemical)/cm^2	mega joule/m^2 (MJ/m^2)	4.184 000 X E -2
curie	giga becquerel (GBq)*	3.700 000 X E +1
degree (angle)	radian (rad)	1.745 329 X E -2
degree Fahrenheit	degree kelvin (K)	$t_K = (t_{°F} + 459.67)/1.8$
electron volt	joule (J)	1.602 19 X E -19
erg	joule (J)	1.000 000 X E -7
erg/second	watt (W)	1.000 000 X E -7
foot	meter (m)	3.048 000 X E -1
foot-pound-force	joule (J)	1.355 818
gallon (U.S. liquid)	meter^3 (m^3)	3.785 412 X E -3
inch	meter (m)	2.540 000 X E -2
jerk	joule (J)	1.000 000 X E +9
joule/kilogram (J/kg)(radiation dose absorbed)	Gray (Gy)**	1.000 000
kilotons	terajoules	4.183
kip (1000 lbf)	newton (N)	4.448 222 X E +3
kip/inch^2 (ksi)	kilo pascal (kPa)	6.894 757 X E +3
ktap	newton-second/m^2 ($N-s/m^2$)	1.000 000 X E +2
micron	meter (m)	1.000 000 X E -6
mil	meter (m)	2.540 000 X E -5
mile (international)	meter (m)	1.609 344 X E +3
ounce	kilogram (kg)	2.834 952 X E -2
pound-force (lbf avoirdupois)	newton (N)	4.448 222
pound-force inch	newton-meter (N-m)	1.129 848 X E -1
pound-force/inch	newton/meter (N/m)	1.751 268 X E +2
pound-force/foot^2	kilo pascal (kPa)	4.788 026 X E -2
pound-force/inch^2 (psi)	kilo pascal (kPa)	6.894 757
pound-mass (lbm avoirdupois)	kilogram (kg)	4.535 924 X E -1
pound-mass-foot^2 (moment of inertia)	kilogram-meter^2 ($kg-m^2$)	4.214 011 X E -2
pound-mass/foot^3	kilogram/meter^3 (kg/m^3)	1.601 846 X E +1
rad (radiation dose absorbed)	Gray (Gy)**	1.000 000 X E -2
roentgen	coulomb/kilogram (C/kg)	2.579 760 X E -4
shake	second (s)	1.000 000 X E -8
slug	kilogram (kg)	1.459 390 X E +1
torr (mm Hg, 0° C)	kilo pascal (kPa)	1.333 22 X E -1

*THE BECQUEREL (BQ) IS THE SI UNIT OF RADIOACTIVITY; 1 BQ = 1 EVENT/S.

**THE GRAY (GY) IS THE SI UNIT OF ABSORBED RADIATION.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

SECTION 1

INTRODUCTION

There is a compelling need for hard, nonvolatile semiconductor memories for future strategic systems and for space defense initiative (SDI) systems. The most acceptable semiconductor memory currently available is based on plated wire. Due to the high cost of plated wire, NDRO core memory is also being explored as a possible alternative. Research and development programs are being pursued in an attempt to develop magneto-resistive memories and two-dimensional plated magnetic memories. So far these programs have only met with limited success.

Recently, ferroelectric memories have been developed (Ref.1) which seem to have all the essential physical and electronic properties to provide hard, nonvolatile semiconductor memories. These memories will have immediate utility for all nonvolatile semiconductor memory applications. They will also have immediate utility for all nonvolatile requirements where the radiation environment is compatible with surface or atmospheric requirements such as Army, Navy and Air Force tactical requirements, avionic requirements, and space natural environment requirements. These memories will also have immediate utility for DRO, nonvolatile, hardened memories for all military requirements. Some development will be necessary to provide hardened nonvolatile NDRO memories for strategic and SDI applications, in that EDAC software, or partial sensing (NDRO sensing) or differential partial sensing against a reference cell must be provided. Of these possibilities EDAC is probably the simplest and most direct and will simultaneously resolve the SEU issue should the ferroelectric capacitor memory cells ever become small enough to have a SEU problem.

Presently, a 512-bit test chip with special circuitry has been fabricated which enables testing the ferroelectric capacitors (Figure 1). This chip is built by purchasing "standard" technology CMOS chips which contain transistors for electrical isolation, addressing, driving, and decoding, and series sense capacitors which provide voltage divider action to provide nodes for sensing with a differential op-amp. A 2K x 8 version has been designed and fabricated which combines the versatility of a RAM with the nonvolatile advantage of a ROM. A 256K RAM based on extending the current 16K version is planned.

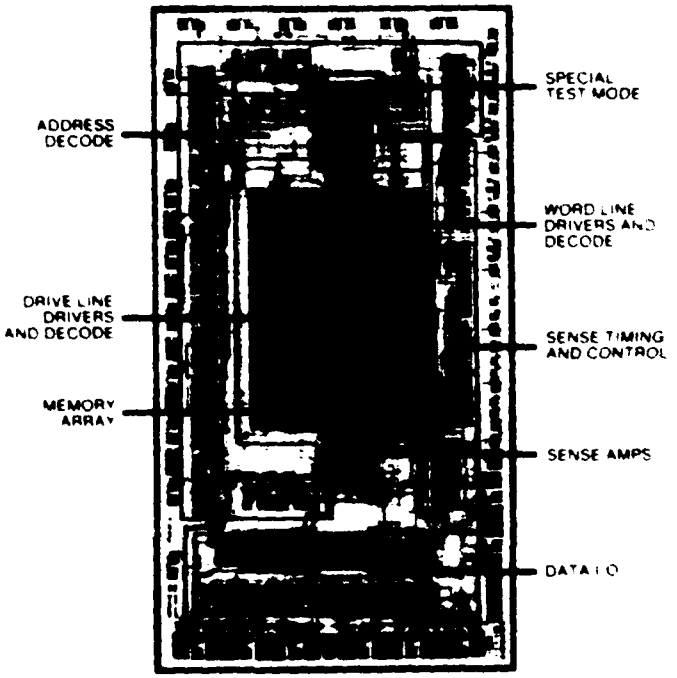


Figure 1. 512-bit nonvolatile memory.

SECTION 2

BASIC MECHANISMS

The ferroelectric effect occurs in materials where the basic crystal allows ionic polarization, (Ref. 2). An applied electric field produces a very small relative movement of one of the atoms in the unit cell, and this displacement persists after the field is removed. This 'ionic' polarization results in a hysteresis curve which resembles ferromagnetic hysteresis although the element iron is seldom present. Figures 2a and 2b are hysteresis curves. Notice it is not as "square" as a good ferromagnetic hysteresis loop.

Polarization is measured in units of charge/cm^2 and the field across the capacitor is measured in volts/cm. A facile even though oversimplified explanation of the memory operation is to recognize that in the saturated polarization condition P_s, the application of a field in the direction of the polarization will not change the 'ionic' polarization very much and the capacitor will respond with a capacitance $\approx C_s$. However, if a reverse field is applied, the ionic polarization will change to P_r, which means that a charge approximately equal to the integrated charge within the hysteresis loop will appear in addition to the normal response of the capacitor $\approx C_s$. That is, a field in one direction produces a response defined by $\approx C_s$ and in the other direction $\approx C_s - C_p$.

The sample capacitors tested in the radiation environment were about 6μ x 9μ x 0.6μ and had values of $P_s - P_r \approx 15\mu c/cm^2$.

There have been many previous attempts to utilize the ferroelectric hysteresis loop for memory storage. For example, $BaTiO_3$ has been extensively studied (Ref. 2). The problem

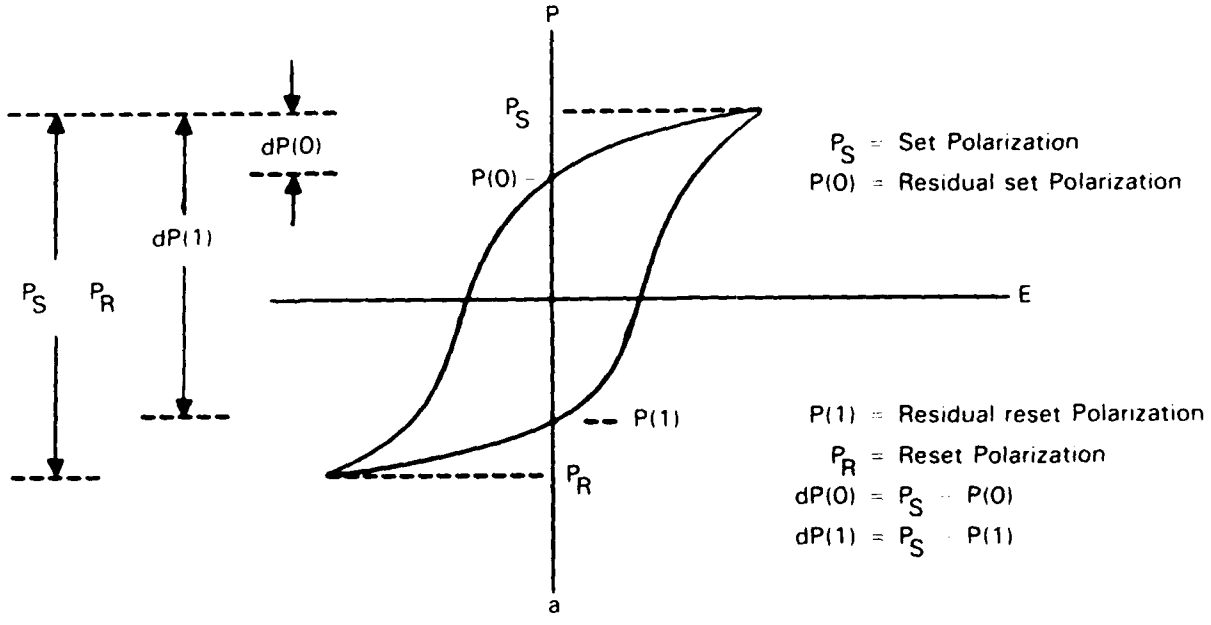


Figure 2a. The hysteresis loop at a ferroelectric capacitor.

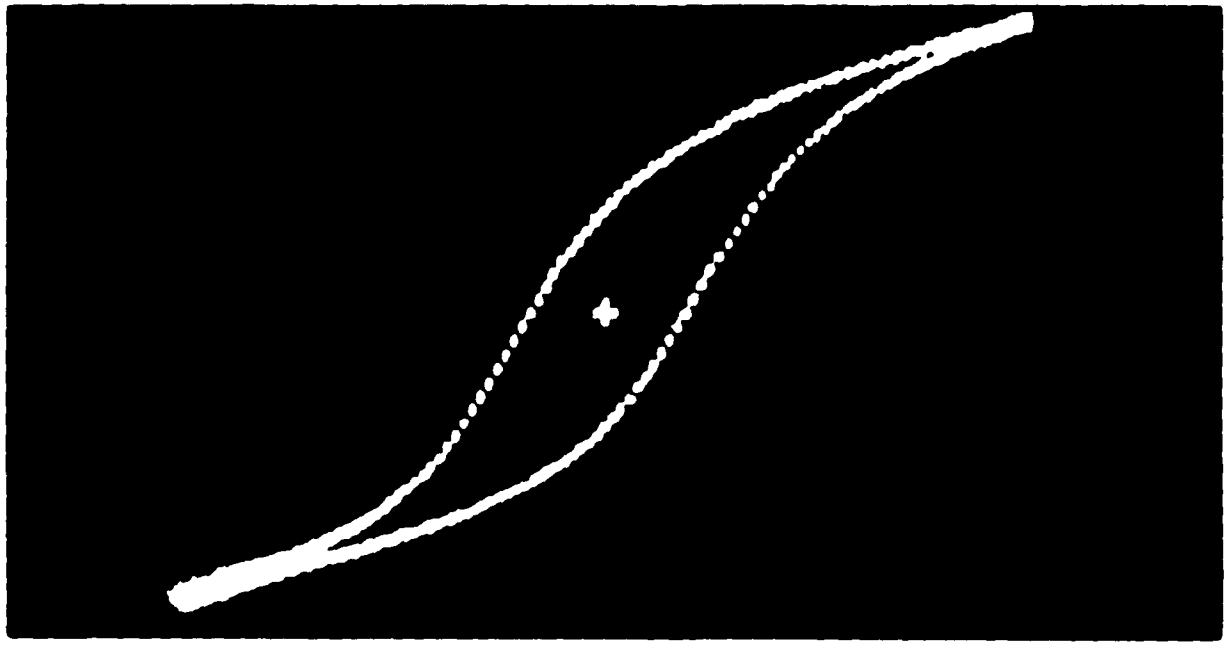


Figure 2b. Ferroelectric hysteresis curve scope trace.

up to now has been fatigue; that is, the polarization phenomenon tends to decrease and disappear after a number of reversals. This is obviously bad news for a RAM. However, the recent results from the specially doped $PbTiO_3$ "perovskite" ceramics with ferroelectric characteristics have shown exceptionally good "fatigue" characteristics. Figures 3a and 3b show the $BaTiO_3$ lattice which is an example of a simple perovskite crystal. A more complex perovskite lattice, a chemically modified (i.e., doped) lead titanate, has been developed to meet the practical requirements of memory applications. The present state-of-the-art is shown in Table 1 (Ref. 1). Research to improve this is continuing. However, the present state-of-the-art will allow continuous read-write operations for the order of approximately 10 years.

The basic dielectric constant of a ferroelectric cell is related to the polarization as follows (Ref. 2):

$$K - 1 = \frac{P}{\epsilon_o E} \tag{1}$$

where K is dielectric constant, P is polarization, ϵ_o is the permittivity of free space, and E is the field used to produce the polarization.

The capacitance of the memory structure is given by

$$C = \frac{K\epsilon_o A}{d} \tag{2}$$

where A is the area of the capacitor and d is the thickness. For $K >> 1$

$$C = \frac{AP}{Ed} \approx \frac{AP}{V} \tag{3}$$

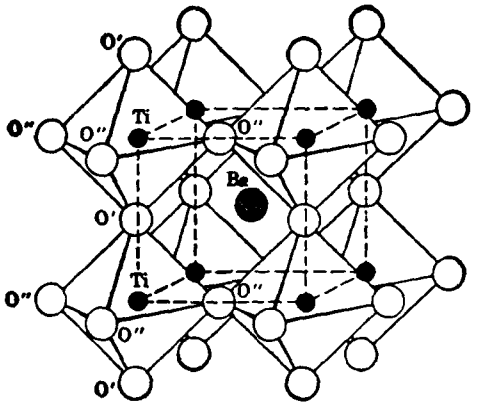


Figure 3a. The $BaTiO_3$ structure, showing the octahedra of oxygen atoms about the titanium atoms (Ref. 5).

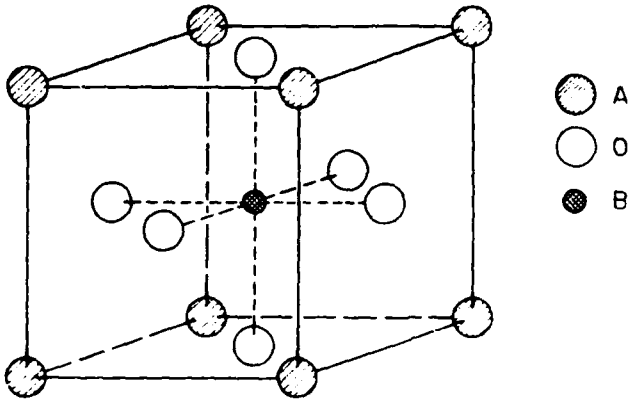


Figure 3b. Cubic Perovskite-type structure ABO_3 (Ref. 5).

Table 1. Properties of doped $PbTiO_3$ ferroelectric material. (Ref 1.).

Initial remanent polarization	5	$\mu C/cm^2$
Initial saturation polarization	15	$\mu C/cm^2$
Remanent polarization at 10^{12} write cycles	1	$\mu C/cm^2$
Saturation Polarization at 10^{12} write cycles	5	$\mu C/cm^2$
Remanent polarization loss <40% in 10 years*		
Coercive Field	50	MV/cm
Switching time at 120 MV/cm applied field	≤5	ns
Dielectric strength	>800	MV/cm
Curie temperature	>300	°C

1. Polarization measurements done with 1 μs pulse drive using a Sawyer-Tower circuit.

2. "Write Cycles" denotes full drive field polarization reversal. This is the worst-case condition of continuous writing with data state reversal on each cycle.

3. Coercive field denotes the point where the hysteresis loop passes through zero polarization. This measurement was done with a 100 KHz AC field applied.

4. Data given assumes room temperature measurement unless otherwise noted.

*40% less results in no loss of digital data.

Again for the newly developed ferroelectric capacitors the capacitance is approximately 1 PF, and the dielectric constant approximately 10^3.

Ferroelectric phenomena have a Curie temperature above which the polarization disappears. This temperature is in excess of 300°C for the ferroelectric capacitors discussed in this paper. This is safely above the normal military application range.

The dielectric constant varies as $1/(T-T_c)$ near the Curie point. It does not go to infinity at T_c of course; the ferroelectric effect simply disappears. Measuring the dielectric constant on both sides of the Curie point allows one to determine if the phase transition is first order or second-order. For some ferroelectrics the transition appears too complex for easy explanation by either first or second-order processes.

SECTION 3

FERROELECTRIC MATERIALS FOR IC MEMORY APPLICATIONS AND FERROELECTRIC MEMORY FABRICATION

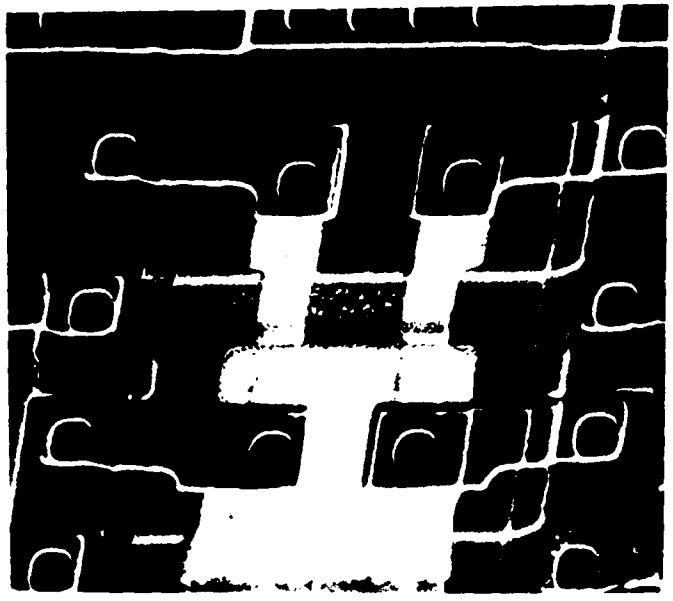
3.1 FERROELECTRIC MATERIAL.

Several boundary conditions are placed on the properties of a ferroelectric storage medium to be used in a practical integrated circuit memory application. Along with the requirement for an acceptable rate of fatigue already mentioned memory applications require acceptable storage temperature range, data retention, switching voltage, switching speed, and dielectric integrity. The material must also be suitable for integration with semiconductor devices without creating contamination problems and must be compatible with integrated circuit fabrication methods.

Ferroelectric ceramics have temperature and environmental stability well suited to integrated circuit applications and the properties of ferroelectric ceramics can be tailored by impurity doping (Ref. 7). A specially doped Lead Titanate was developed specifically to meet the requirements of the integrated circuit memory application. Some of the relevant properties of this material are listed in Table 1.

3.2 FABRICATION.

Ferroelectric storage capacitors are integrated with CMOS to produce a full integrated circuit with a JEDEC standard SRAM interface. This is accomplished by fabricating a parallel plate ferroelectric capacitor atop interlevel glass normally used to separate the semiconductor portion of a circuit from the first-level metal interconnect (see Figure 4).



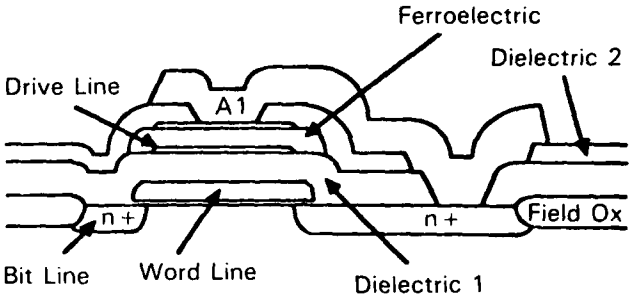


Figure 4. A scanning electron micrograph showing the first storage capacitor on each of a pair of rows in a memory array. The aluminum interconnects from the top electrodes of the ferroelectric capacitors to the source of the pass transistor is seen near the top of the micrograph. The aluminum interconnect from the drive line decoder to the bottom electrode metal, which runs along the row beneath the ferroelectric film, is shown near the bottom of the micrograph. The polysilicon word lines run up either side of the micrograph along each row. The bit line crossing the bottom metal drive lines is diffusion which is seen as a depression in the horizontal direction. The bit line crossing the poly word lines is aluminum seen making contact to the diffusion just below the pass transistor gate.

SECTION 4

RADIATION EFFECTS

The discussion previously presented allows radiation effects to be calculated based on the underlying physics, geometry and electronics. This will now be done and comparisons made with preliminary experimental measurements (Ref. 3). In anticipation of these results, it is here noted that the radiation tolerance of a complete memory cell will be determined by the radiation hardness of the semiconductor devices used in the auxiliary circuits, e.g., I/O circuits, sense circuits and write circuits. This is because the actual ferroelectric capacitor storage elements are extremely radiation hard.

4.1 DISPLACEMENT DAMAGE.

The basic ferroelectric effect is a cooperative phenomenon involving the summation of effects from the individual basic cells or 'unit cells.' The capacitors are so thin that 'domain' wall motion is a second-order effect, and the primary effect is the direct polarization of all of the cells in the capacitor. The domain walls are nearly all perpendicular to the ferroelectric film (see Figure 5). For the purpose of a semi-quantitative calculation of neutron damage threshold the unit cell volume will be estimated at 5×10^{-6} cm x 5×10^{-8} cm x 5×10^{-8} cm or 125×10^{-24} cm^3. There are then about

$$\frac{1}{125 \times 10^{-24}} \qquad (4)$$

cells/cm^3 or 8×10^{21} cells/cm^3. The damage threshold will

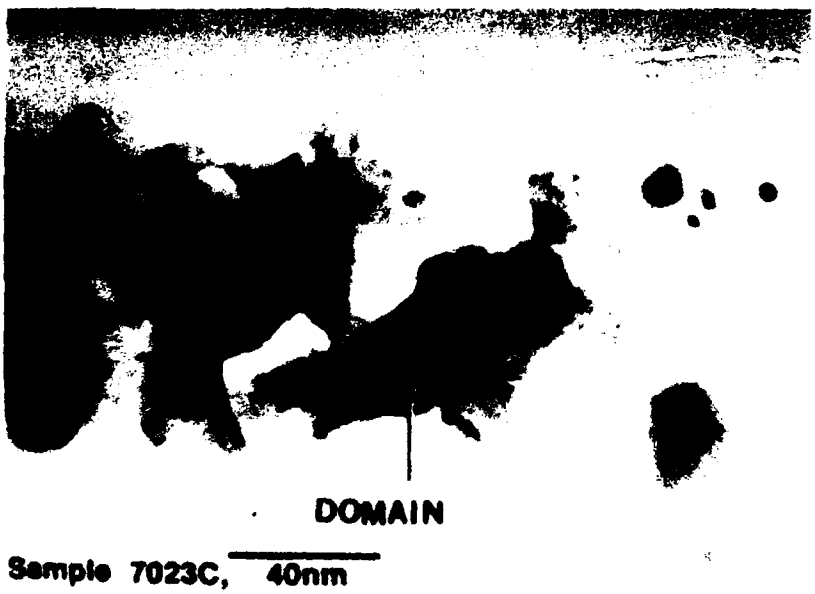


Figure 5. Thin film ferroelectric domain structure.

occur when displacement damage disturbs about 1% of the volume or amounts to about 8 x 10^{19} displacements/cm^3. The neutron displacement cross section is very roughly 5 x $10^{-24}/cm^2$ and the density of damage regions is given by $Nd = N_a \sigma_D \Phi \bar{\eta}$. $\bar{\eta}$ is a multiplication factor which is approximately 500 for 1 MeV neutrons. The atomic density is approximately 5 x 10^{22} atoms/cm^3 and so the neutron fluence required to produce about 10^{19} displacements/cm^3 is approximately 6.4 x 10^{17} n/cm^2. At this level other effects would certainly predominate. In particular the ionic polarization is a strong function of the lattice constant. The lattice constant must be small enough so that the atom which "slips" a small distance in the unit cell between two relatively stable limit positions (P_s and P_v) will remain quasi-stable in each polarization position yet it must be large enough so that "slippage" is possible at all. Only a very narrow range of lattice constants satisfies this condition. If one assumes a linear coefficient of expansion due to neutron exposure of the form (Ref. 4)

$$\frac{\Delta \ell}{\ell} \approx \kappa \Phi \qquad (5)$$

with worst case κ approximately 5 x $10^{-19}/n/cm^2$ (Ref. 5) and if one further assumes that a change of 0.1% is the lattice constant that will appreciably change the ferroelectric hysteresis curve, then the damage threshold is approximately 5 x $10^{+16} n/cm^2$. Again, there is no significant concern at military requirement levels. The limit 0.1% is chosen to be small compared with the distance the titanium atom moves when polarization is reversed ($\approx$0.5A°) and also comparable to the change in lattice

parameters over a 200°C temperature range (≈0.5A°) (Ref. 5) The limit 0.1% is also consistent with a lattice strain of 0.3% observed as a consequence of full polarization.

4.2 PROMPT DOSE RATE.

A prompt pulse could affect the polarization state if it allowed the polarization field to relax for a sufficiently long time. To estimate the threshold for this effect one compares the charge density from the polarization to the charge density created by the radiation pulse. If the radiation charge exceeds the polarization charge, the internal field in the ferroelectric could relax and be altered and the polarization could change. The charge from the radiation is estimated from

$$Q_\gamma = gyv \approx 1.6 \times 10^{-19} \times 10^{13} \times 54 \times 10^{-8} \times 4 \times 10^{-4} \approx 32 \times 10^{-16} \text{ coulombs/rad} \quad (6)$$

The charge from the polarization is

$$Q_p = PA = 15 \times 10^{-6} \times 54 \times 10^{-8} = 810 \times 10^{-14} \text{ coulombs}$$

The prompt radiation pulse required to make $Q_\gamma \approx Q_p$ is then 810×10^{-14} coulombs 32×10^{-16} coulombs/rad or approximately 250,000 rads. Some changes in the polarization might occur at about 10% of this level or 25,000 rads. This is a worst-case analysis since the polarization charge is ionic and the radiation charge electronic. Presumably the radiation charge will not be 100% effective in neutralizing the ionic polarization charge since it will be highly mobile and will be rapidly swept out of the memory cell. Another estimate of the electronic charge required to relax the polarization can be generated from the write pulse descrip-

tion and requirements. The write field is applied for 50 nsec. The charge transit time through the ferroelectric capacitor is given by

$$\frac{d^2}{\mu V} \qquad (7)$$

where μ is estimated as 1 cm^2/volt sec. Using these values, the transit time is $(.6 \times 10^{-4})^2/1.00 \times 5 \approx 7 \times 10^{-10}$ seconds. The ratio of the write time to the transit time is approximately 70, and one therefore concludes that in the "worst-case" the electrons are about 1% effective in altering ionic polarization. An estimate of 10% effective would lead to a calculated threshold of 250,000 rads prompt.

The required duration of the applied field can be estimated from basic ferroelectric theory. For example, it has been shown that the displacement of the Titanium atom in $BaTiO_3$ must be 0.26×10^{-8} cm if one attributes all of the polarization to this shift. The Titanium atom itself has a charge of +4 in the lattice.

The Ti^{++++} ion moves in the unit cell between two oxygen atoms. There are two stable polarization positions, a saturated polarization and a reset polarization state. The Ti^{++++} moves in a potential well whose specific shape can be deduced from the nature of the phase transition at the Curie temperature. Measurement of the dielectric constant as a function of $T-T_c$ will define a first order, second order, or sometimes an even more complicated phase transition. Qualitatively, the potential well is depicted in Figure 6.

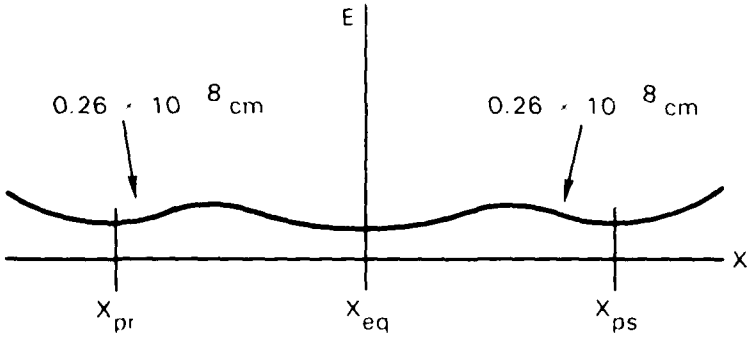


Figure 6. Qualitative picture of the potential well for the Ti^{++++} atom (Ref. 6).

The dynamics of the establishment of the transition (write) times can be deduced by solving an approximate form of the equation of motion of the Ti^{++++} atom. This assumes that domain wall motion effects do not significantly affect switching times. This assumption is consistent with the observation that domain walls are predominantly perpendicular to the capacitor film (see Fig. 5). In the equilibrium position X_{eq}, the forces on the Ti^{++++} atom are 0. At X_{ps} the polarization force 4eE is balanced by a lattice restoring force which must be equal and opposite to the polarization force. If the variation of E with X is neglected, since the maxima between X_{eq} and either X_{ps} or X_{pr} are quite small, the equation of motion is

$$X^{11} - AX^{1} - \frac{4eE}{Km}\left(\frac{X_e - X}{X_e}\right) = 0 \qquad (8)$$

for moving the Ti^{++++} atom from X_{eq} to X_{ps}. The term AX^{1} is lattice "friction" force which damps out the oscillation which the Ti^{++++} atom would otherwise experience. An approximate solution is

$$X - X_{eq} = X_{eq} \exp\left(-\frac{At}{2}\right)\cos\left(\frac{4eE}{mX_{eq}K}\right)^{1/2} t \qquad (9)$$

The half cycle time or write time is

$$t = \frac{\pi}{4}\sqrt{\frac{mX_{eq}K}{eE}} \quad . \qquad (10)$$

The same approximation gives the switching time from X_{ps} to X_{pr} since both the distance and the initial acceleration are doubled and $t^2 \approx \frac{2x}{g}$. This approximation for switching time neglects the "friction" term, AX^1, which will tend to slow the transition down slightly and rapidly damp out the oscillation which would otherwise ensue.

This calculation also shows that a minimum write time of approximately 0.1 nsec puts an upper limit on the memory speed unless the capacitor thickness d can be substantially reduced. However, this limit is so fast that it will not be a problem for the foreseeable future. It should be noted that a practical circuit would require write times at least an order of magnitude larger (~1 ns) to provide design margin. It should be noted here that the atomic mass of titanium and the displacement of titanium in $BaTiO_3$ were both used in the calculation. The current ferroelectric material situation uses a modified $PbTiO_3$ ceramic and therefore the polarization is similar; however, the specific composition of this ferroelectric material has not been released.

4.3 TOTAL DOSE.

No specific total dose damage mechanism other than eventual displacement damage from high-energy Compton electrons is

foreseen. On this basis the threshold for total dose resulting from high energy γ radiation is estimated to be greater than 10^8 rads(Si). This exceeds the capability of the associated silicon circuits and is much greater than any currently projected military requirements.

4.4 OTHER RADIATION EFFECTS

The ceramic contains lead, a high Z material, and so thermo-mechanical shock from X-rays and dose enhancement are both second-order effects which must be considered. Both are amenable to shielding.

SECTION 5

SINGLE EVENT UPSET

The large polarization charge density makes the memory cell relatively impervious to SEU for a reasonable geometry. The SEU sensitivity can be estimated based on the calculations already made. First the charge density must exceed the polarization charge. The polarization charge is 8.1 p coulombs for our 6μ by 9μ ferroelectric capacitor. Typical charge deposition from α particles would be 0.1 p coulombs, for Cu about 2 p coulombs (Ref. 7). For α particles to affect the polarization, the area of the capacitor would have to be about 81 times smaller (approximately 0.8μ by 0.8μ). However, α charge collection times would be about 1/2 nsec (Ref. 7) and, although some depolarization might take place, it would probably be relatively small. Charge collection from Cu ions would take 3 or 4 nsec. In addition, Cu ions would supply far more charge. Furthermore, the available charge would depend on the angle of incidence of the incoming high Z particles.

Significant depolarization might occur for 3μ by 4μ capacitors for heavy ions. This is a worst-case estimate. The data from fission fragments support that the SEU sensitivity is much lower than this estimate.

However, the question of permanent damage to a capacitor under high electric field, similar to observed MNOS and MOS failure at high fields, must be resolved experimentally.

SECTION 6
EXPERIMENTAL RADIATION EFFECTS DATA COMPARED WITH THEORY

A small number of experimental tests have been run on ferroelectric capacitors in the radiation environment. The results are consistent with the preceding discussion. Unfortunately, radiation stresses sufficient to damage the hysteresis loop have not been tested so the experimental results merely define levels at which no damage is observed and show that much higher levels will be required to damage the basic memory cell (see Table 2).

Table 2. Comparison of theoretical and experimental radiation data.

RADIATION STRESS	DISPLACEMENT DAMAGE, n/cm^2	IONIZING DOSE, Rads(Si)	IONIZING DOSE, Rads(Si)/s	FISSION FRAGMENTS Cf-252, $Particles/cm^2$
THEORETICAL THRESHOLD (ESTIMATED LEVEL THRESHOLD)	5×10^{16}	$>10^8$	2.5×10^{13}	PROBABLY NO DAMAGE, NO SEU AT ANY LEVEL
EXPERIMENTAL DATA (MEASURED LEVEL AT WHICH NO DAMAGE IS OBSERVED)	10^{14}	10^7	1.2×10^{11}	At 6×10^6 Particles cm^2, NO DAMAGE AND NO SEU

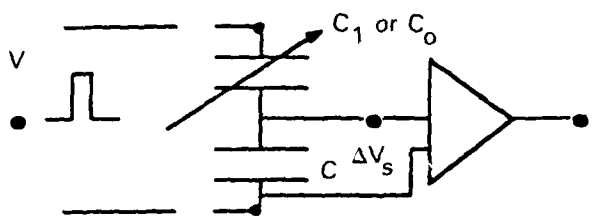
SECTION 7

READ MECHANIZATION

The simplest read circuit puts the ferroelectric capacitor in series with a standard capacitor (Figure 7a). The ferroelectric capacitor is then sensed with a field sufficient to produce saturation polarization. The signal at the node of the sensing capacitor is fed into an op-amp. If the cell is already in the saturated state only a small signal results. If the cell is in the reset polarization state a larger signal results.

Actually, to improve noise margins a Ferroelectric Reference Capacitor is used and a differential sense mode between the sensor capacitor and reference ferroelectric capacitor is employed. The functional diagram and timing diagram for a typical application are shown in Figures 7b and 7c.

To make the read cycle as immune to radiation pulse upset as possible, the read/restore process can be done on a bit-by-bit basis with the total cycle lasting about 50 nsec. The probability of being hit by two successive radiation pulses/within 50 ns is vanishingly small for any practical nuclear scenario. If a bit is destroyed by interruption of a single read/restore cycle, a software fix utilizing a flag to identify the bit being read, a word sum using a *Hamming* code technique or parity bit technique can determine if the bit must be reset. Thus, utilization of a rapid read/restore cycle enables the memory to effectively become NDRO in any practical scenario. There are of course other schemes to make the memory NDRO, such as partial sensing or differential sensing against a reference. However, the EDAC scheme is probably the simplest and most practical.



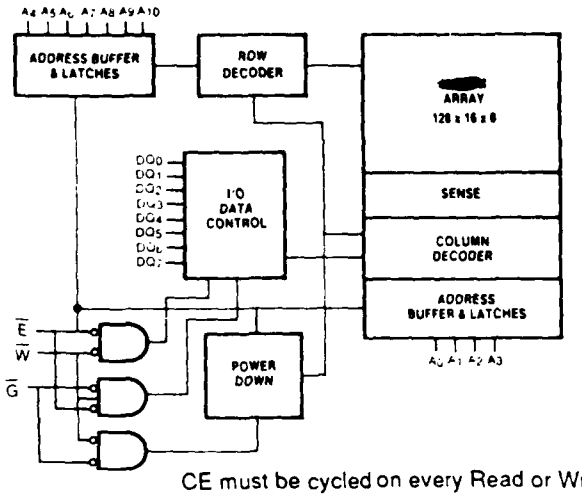
$$C = \frac{\Delta(P(s) - P_o)}{V_{in}}$$

$$C_o = \frac{\Delta(P(s) - P_1)}{V_{in}}$$

$$\Delta V_s = \Delta(P_s - P_o)/C$$

$$\Delta V_{so} = \Delta(P_s - P_1)/C$$

Figure 7a. Sample sensing circuit.



CE must be cycled on every Read or Write access regardless of history.

Figure 7b. Functional diagram.

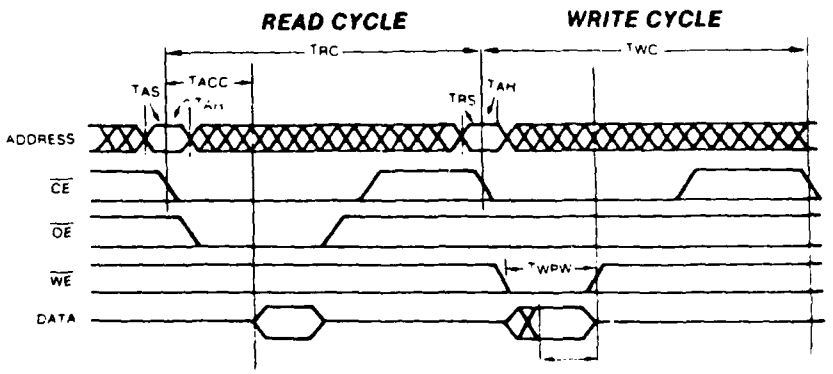


Figure 7c. Timing diagram.

SECTION 8

LIST OF REFERENCES

1. Evans, Miller and Bullington, "International Electron Devices Technical Meeting," Washington, DC, 1987.

2. Feynman, R.P., The Feynman Lectures on Physics, Addison Wesley, 1963.

3. Wrobel, Bullington and Schweer, "Radiation Hardness Evaluation of Thin Film Ferroelectric Capacitors," (to be published).

4. Bullington, D and Crawford, J., Radiation Damage in Solids, Princeton University Press, 1961.

5. Landolt-Börnstein, "Numerical Data and Functional Relationships in Science and Technology," Group III: Crystal and Solid State Physics, Volume 16, Ferroelectric and Related Substances, Subvolume A: Oxides, p. 468, Figure 396.

6. Kittel, C., Introduction to Solid State Physics, 4th ed., John Wiley & Sons, 1971.

7. Messenger, G., "Collection of Charge on Junction Nodes from Ion Tracks, "IEEE Tran. on Nuc. Sci., Vol. NS-29, No. 6, 2024-2031, December 1982.

DISTRIBUTION LIST
DNA-TR-88-94

DEPARTMENT OF DEFENSE

ASSISTANT TO THE SECRETARY OF DEFENSE
ATOMIC ENERGY
ATTN: EXECUTIVE ASSISTANT

DEFENSE ELECTRONIC SUPPLY CENTER
ATTN: DEFC-EAA

DEFENSE INTELLIGENCE AGENCY
ATTN: DT-1B
ATTN: RTS-2B

DEFENSE LOGISTICS AGENCY
ATTN: DLA-QEL W T HUDDLESON

DEFENSE NUCLEAR AGENCY
ATTN: RAEE (TREE)
4 CYS ATTN: TITL

DEFENSE TECHNICAL INFORMATION CENTER
12CYS ATTN: DTIC/FDAB

DNA PACOM LIAISON OFFICE
ATTN: DNALO

FIELD COMMAND DEFENSE NUCLEAR AGENCY
ATTN: FCPF R ROBINSON
ATTN: TDTT

JOINT DATA SYSTEM SUPPORT CTR
ATTN: R MASON
ATTN: C-330

JOINT STRAT TGT PLANNING STAFF
ATTN: JKCS, STUKMILLER
ATTN: JPEP
ATTN: JPTM

LAWRENCE LIVERMORE NATIONAL LABORATORY
ATTN: DNA-LL

NATIONAL COMMUNICATIONS SYSTEM
ATTN: NCS-TS

UNDER SECRETARY OF DEFENSE
ATTN: G SEVIN

DEPARTMENT OF THE ARMY

HARRY DIAMOND LABORATORIES
ATTN: SLCHD-NW-RC
ATTN: SLCHD-NW-RH

NUCLEAR EFFECTS DIVISION
ATTN: R WILLIAMS

U S ARMY BALLISTIC RESEARCH LAB
ATTN: SLCBR-VL D RIGOTTI

U S ARMY COMMUNICATIONS R&D COMMAND
ATTN: DRSEL-NL-RO R BROWN

U S ARMY ELECTRONIC TECH DEV LAB
ATTN: SLCET-SI R ZETO

U S ARMY ENGINEER DIV HUNTSVILLE
ATTN: HNDED-ED J HARPER

U S ARMY GARRISON
ATTN: LIBRARY

U S ARMY MATERIAL TECHNOLOGY LABORATORY
ATTN: DRXMR-B J HOFMANN
ATTN: DRXMR-HH J DIGNAM

U S ARMY MISSILE COMMAND
ATTN: AMCPM-HA-SE-MS

U S ARMY MISSILE COMMAND/AMSMI-RD-CS-R
ATTN: AMSMI-RD-CS-R (DOCS)

U S ARMY NUCLEAR & CHEMICAL AGENCY
ATTN: MONA-NU

U S ARMY RESEARCH OFFICE
ATTN: R GRIFFITH

U S ARMY STRATEGIC DEFENSE CMD
ATTN: BMDSC-AV J HARPER
ATTN: DASD-H-YA

U S ARMY TEST AND EVALUATION COMD
ATTN: AMSTE-

U S ARMY WHITE SANDS MISSILE RANGE
ATTN: STEWS-TE-AN A DE LA PAZ

XM-1 TANK SYSTEM
ATTN: DRCPM-GCM-SW

DEPARTMENT OF THE NAVY

NAVAL AIR SYSTEMS COMMAND
ATTN: AIR 350F
ATTN: AIR 931A

NAVAL AVIONICS CENTER
ATTN: CODE B455 D REPASS

NAVAL ELECTRONICS ENGRG ACTVY, PACIFIC
ATTN: CODE 250 D OBRYHIM

NAVAL INTELLIGENCE SUPPORT CTR
ATTN: NISC LIBRARY

NAVAL OCEAN SYSTEMS CENTER
ATTN: CODE 9642 TECH LIB

NAVAL POSTGRADUATE SCHOOL
ATTN: CODE 1424 LIBRARY

NAVAL RESEARCH LABORATORY
ATTN: CODE 5813 W JENKINS
ATTN: CODE 6810 J KILLIANY

NAVAL SURFACE WARFARE CENTER
ATTN: CODE H21 F WARNOCK

NAVAL SURFACE WARFARE CENTER
ATTN: CODE H-21

NAVAL UNDERWATER SYS CENTER
ATTN: 8092

NAVAL WEAPONS CENTER
ATTN: CODE 343

NAVAL WEAPONS EVALUATION FACILITY
ATTN: CLASSIFIED LIBRARY

NAVAL WEAPONS SUPPORT CENTER
ATTN: CODE 605 J RAMSEY

OFC OF THE DEP ASST SEC OF THE NAVY
ATTN: L J ABELLA

OFC OF THE DEPUTY CHIEF OF NAVAL OPS
ATTN: NOP 985F

OPERATIONAL TEST & EVALUATION FORCE
ATTN: CODE 80

SPACE & NAVAL WARFARE SYSTEMS CMD
ATTN: CODE 50451
ATTN: NAVELEX 51024 C WATKINS
ATTN: PME 117-21

DEPARTMENT OF THE AIR FORCE

AERONAUTICAL SYSTEMS DIVISION
ATTN: ASD/ENES(P MARTH)
ATTN: ASD/ENSS

AIR FORCE CTR FOR STUDIES & ANALYSIS
2 CYS ATTN: AFCSA/SAMI (R GRIFFIN)

AIR FORCE INSTITUTE OF TECHNOLOGY/EN
ATTN: AFIT/ENP C BRIDGMAN

AIR FORCE SYSTEMS COMMAND
ATTN: DLCAM
ATTN: DLW

AIR FORCE WEAPONS LABORATORY
ATTN: NTCAS J MULLIS
ATTN: NTCT MAJ HUNT
ATTN: NTCTR R MAIER
ATTN: SUL

AIR FORCE WRIGHT AERONAUTICAL LAB
ATTN: AFWAL/AADE
ATTN: AFWAL/MLTE

AIR UNIVERSITY LIBRARY
ATTN: AUL-LSE

BALLISTIC MISSILE OFFICE
ATTN: ENSE

HILL AIR FORCE BASE
ATTN: TRW/H L DEPT

OGDEN AIR LOGISTICS COMMAND
ATTN: OO-ALC/MMEDD
ATTN: OO-ALC/MMGR

ROME AIR DEVELOPMENT CENTER, AFSC
ATTN: RBR J BRAUER

ROME AIR DEVELOPMENT CENTER, AFSC
ATTN: ESR

SPACE DIVISION/AQ
ATTN: ALT

SPACE DIVISION/CNCIV
ATTN: YN

SPACE DIVISION/YA
ATTN: YAS

SPACE DIVISION/YAR
ATTN: YAR CAPT STAPANIAN

SPACE DIVISION/YD
ATTN: YD

SPACE DIVISION/YE
ATTN: YE

STRATEGIC AIR COMMAND/NRI-STINFO
ATTN: NRI/STINFO

STRATEGIC AIR COMMAND/XPFC
ATTN: XRFC

TACTICAL AIR COMMAND/XPJ
ATTN: TAC/XPJ

3416TH TECHNICAL TRAINING SQUADRON (ATC)
ATTN: TTV

DEPARTMENT OF ENERGY

DEPARTMENT OF ENERGY
ATTN: ESHD

LAWRENCE LIVERMORE NATIONAL LAB
ATTN: TECH INFO DEPT LIBRARY

LOS ALAMOS NATIONAL LABORATORY
ATTN: E LEONARD

SANDIA NATIONAL LABORATORIES
ATTN: B L GREGORY
ATTN: P V DRESSENDORFER
ATTN:T A DELLIN
ATTN: T F WROBEL

OTHER GOVERNMENT

CENTRAL INTELLIGENCE AGENCY
ATTN: OSWR/NED
ATTN: OSWR/STD/MTB

DEPARTMENT OF TRANSPORTATION
ATTN: ARD-350

NASA
ATTN: CODE 313 V DANCHENKO

NATIONAL BUREAU OF STANDARDS
ATTN: T RUSSELL

DEPARTMENT OF DEFENSE CONTRACTORS

ADVANCED RESEARCH & APPLICATIONS CORP
ATTN: L PALKUTI

AEROJET ELECTRO-SYSTEMS CO
ATTN: D TOOMB

AEROSPACE CORP
ATTN: C E BARNES
ATTN: K T WILSON
ATTN: N SRAMEK

AEROSPACE CORPORATION
ATTN: M HOPKINS

ALLIED-SIGNAL INC
ATTN: E MEEDER

ALLIED-SIGNAL, INC
ATTN: DOCUMENT CONTROL

AMPEX CORP
ATTN: P PEYROT

ANALYTIC SERVICES, INC (ANSER)
ATTN: J OSULLIVAN

BDM CORP
ATTN: C M STICKLEY

BDM CORP
ATTN: D WUNSCH

BOEING CO
ATTN: I ARIMURA

BOOZ-ALLEN & HAMILTON, INC
ATTN: R MCCOSKEY

CALIFORNIA INSTITUTE OF TECHNOLOGY
ATTN: W PRICE

CALSPAN CORP
ATTN: R THOMPSON

CHARLES STARK DRAPER LAB, INC
ATTN: N TIBBETTS
ATTN: P GREIFF
ATTN: W D CALLENDER

CINCINNATI ELECTRONICS CORP
ATTN: L HAMMOND

CLARKSON UNIVERSITY
ATTN: P J MCNULTY

COMPUTER SCIENCES CORP
ATTN: A SCHIFF

DAVID SARNOFF RESEARCH CENTER, INC
ATTN: R SMELTZER

DENVER COLORADO SEMINARY UNIVERSITY OF
ATTN: SEC OFFICER FOR

E-SYSTEMS, INC
ATTN: K REIS

E-SYSTEMS, INC
ATTN: DIVISION LIBRARY

EATON CORP
ATTN: R BRYANT

ELECTRONIC INDUSTRIES ASSOCIATION
ATTN: J KINN

FORD AEROSPACE CORPORATION
ATTN: TECHNICAL INFO SRVCS

GENERAL ELECTRIC CO
ATTN: DOCUMENTS LIBRARY
ATTN: TECHNICAL LIBRARY

GENERAL ELECTRIC CO
ATTN: B FLAHERTY
ATTN: G BENDER
ATTN: L HAUGE

GENERAL ELECTRIC CO
ATTN: G GATI

GENERAL ELECTRIC CO
ATTN: C HEWISON

GENERAL ELECTRIC CO
ATTN: J MILLER

GENERAL ELECTRIC COMPANY
ATTN: D TOSC4

GENERAL RESEARCH CORP
ATTN: A HUNT

GEORGE WASHINGTON UNIVERSITY
ATTN: A FRIEDMAN

GRUMMAN AEROSPACE CORP
ATTN: J ROGERS

GTE GOVERNMENT SYSTEMS CORPORATION
ATTN: J A WALDRON

HARRIS CORP
ATTN: J W SWONGER

HARRIS CORPORATION
ATTN: W ABARE

HONEYWELL, INC
ATTN: MS 725-5
ATTN: MS 830-4A

HONEYWELL, INC
ATTN: D HEROLD

HONEYWELL, INC
ATTN: R BELT

HUGHES AIRCRAFT CO
ATTN: W SCHENET

HUGHES AIRCRAFT CO
ATTN: J HALL

HUGHES AIRCRAFT COMPANY
ATTN: E KUBO
ATTN: L DARDA

IBM CORP
ATTN: H MATHERS

IBM CORP
ATTN: J ZIEGLER

IBM CORP
ATTN: A EDENFELD
ATTN: N HADDAD

IIT RESEARCH INSTITUTE
ATTN: A VALENTINO, DIR
ATTN: I MINDEL

ILLINOIS COMPUTER RESEARCH, INC
ATTN: E S DAVIDSON

INSTITUTE FOR DEFENSE ANALYSES
ATTN: TECH INFO SERVICES

IRT CORP
ATTN: N J RUDIE

IRT CORP
ATTN: J AZAREWICZ

JAYCOR
ATTN: T FLANAGAN

JAYCOR
ATTN: R SULLIVAN

JAYCOR
ATTN: C ROGERS

JOHNS HOPKINS UNIVERSITY
ATTN: R MAURER

JOHNS HOPKINS UNIVERSITY
ATTN: G MASSON

KAMAN SCIENCES CORP
ATTN: K LEE

KAMAN SCIENCES CORP
ATTN: DIR SCI & TECH DIV

KAMAN SCIENCES CORP
ATTN: E CONRAD

KAMAN SCIENCES CORPORATION
ATTN: D PIRIO

KAMAN SCIENCES CORPORATION
ATTN: DASIAC

KAMAN TEMPO
ATTN: DASIAC

LITTON SYSTEMS INC
ATTN: E L ZIMMERMAN
ATTN: F MOTTER

LOCKHEED MISSILES & SPACE CO, INC
ATTN: REPORTS LIBRARY

LOCKHEED MISSILES & SPACE CO, INC
ATTN: B KIMURA

MAGNAVOX ADVANCED PRODUCTS & SYS CO
ATTN: W HAGEMEIER

MARTIN MARIETTA CORP
ATTN: TIC

MARTIN MARIETTA CORP
ATTN: S BUCHNER
ATTN: T DAVIS

MARTIN MARIETTA DENVER AEROSPACE
ATTN: RESEARCH LIBRARY

MARYLAND, UNIVERSITY OF
ATTN: H C LIN

MCDONNELL DOUGLAS CORP
ATTN: A P MUNIE
ATTN: D L DOHM

MCDONNELL DOUGLAS CORP
ATTN: P ALBRECHT

MCDONNELL DOUGLAS CORP
ATTN: TECHNICAL LIBRARY

MISSION RESEARCH CORP
ATTN: C LONGMIRE

MISSION RESEARCH CORP
ATTN: R PEASE

MISSION RESEARCH CORP
ATTN: J LUBELL

MISSION RESEARCH CORP, SAN DIEGO
ATTN: J RAYMOND

MOTOROLA, INC
ATTN: A CHRISTENSEN

NATIONAL SEMICONDUCTOR CORP
ATTN: F C JONES

NORDEN SYSTEMS, INC
ATTN: TECHNICAL LIBRARY

NORTHROP CORP
ATTN: J SROUR

NORTHROP CORP
ATTN: E KING

PACIFIC-SIERRA RESEARCH CORP
ATTN: H BRODE, CHAIRMAN SAGE

PHYSICS INTERNATIONAL CO
ATTN: J SHEA

R & D ASSOCIATES
2 CYS ATTN: G MESSENGER
ATTN: M GROVER

RAND CORP
ATTN: C CRAIN

RAND CORP
ATTN: B BENNETT

RAYTHEON CO
ATTN: G JOSHI
ATTN: J CICCIO

RCA CORP, MICROELECTRONICS CENTER
ATTN: E SCHMITT
ATTN: W ALLEN

RCA CORPORATION
ATTN: G BRUCKER

RESEARCH TRIANGLE INSTITUTE
ATTN: M SIMONS

ROCKWELL INTERNATIONAL CORP
ATTN: TIC 124-203

ROCKWELL INTERNATIONAL CORP
ATTN: T YATES

ROCKWELL INTERNATIONAL CORP
ATTN: D KONO
ATTN: V STRAHAN

S-CUBED
ATTN: J KNIGHTEN

SCIENCE APPLICATION INTL CORP
ATTN: P ZIELIE

SCIENCE APPLICATIONS INTL CORP
ATTN: D MILLWARD
ATTN: R J BEYSTER
ATTN: V ORPHAN

SCIENCE APPLICATIONS INTL CORP
ATTN: J SPRATT

SCIENCE APPLICATIONS INTL CORP
ATTN: W CHADSEY

SINGER CO
ATTN: J D BRINKMAN
ATTN: TECHNICAL INFO CNTR

SUNDSTRAND CORP
ATTN: C WHITE

SYSTEM DEVELOPMENT CORP
ATTN: PRODUCT EVALUATION LAB

SYSTRON-DONNER CORP
ATTN: J RAY

TELEDYNE BROWN ENGINEERING
ATTN: G R EZELL

TELEDYNE SYSTEMS CO
ATTN: R SUHRKE

TEXAS INSTRUMENTS, INC
ATTN: T CHEEK

TRW INC
ATTN: A WITTELES
ATTN: TECH INFO CTR,DOC ACQ

TRW SPACE & DEFENSE SYSTEMS
ATTN: D M LAYTON

TRW SPACE & DEFENSE, DEFENSE SYSTEMS
ATTN: C BLASNEK
ATTN: J GORMAN

UNISYS CORPORATION-DEFENSE SYSTEMS
ATTN: P MARROFFINO

VISIDYNE, INC
ATTN: C H HUMPHREY

WESTINGHOUSE ELECTRIC CORP
ATTN: R CRICCHI

WESTINGHOUSE ELECTRIC CORP
ATTN: S WOOD